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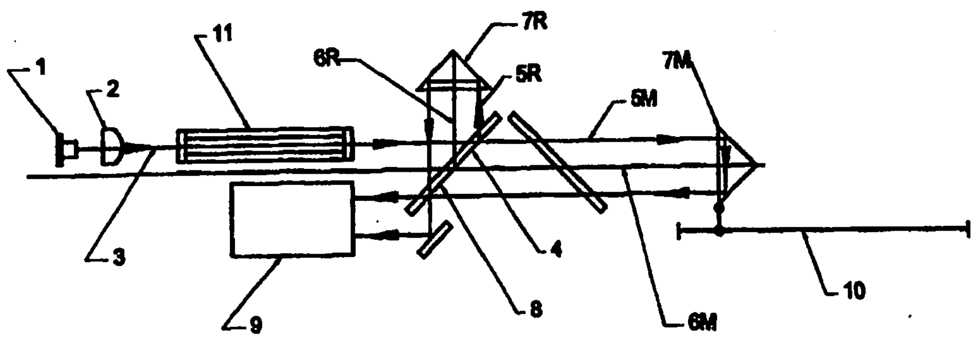

(57) Abstract

An apparatus for the calibration of laser length measuring interferometers using a broad spectral band light source (1) whose spectral composition is modified by a filter (11). The light passes through a length measuring interferometer so that short bursts of fringes are detected at more than one position along a measuring range (10). In the preferred embodiment of the invention, the filter is a Fabry Perot interferometer (11) whose mirror separation sets the interval along the measuring range between which fringe bursts are detected. The fringe bursts are converted into electrical reference signatures by fringe detection means (9) and their positions located with extreme precision by known electronic detection circuitry. The separation of short bursts of detectable fringes in the measuring range have a precise correspondence with separation of the mirrors of the Fabry Perot etalon. The cavity length of the etalon therefore provides an optical length artifact by which the measuring range (10) is calibrated.

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APPARATUS FOR PRECISE LENGTH MEASUREMENT CALIBRATION

This invention relates to apparatus for precise length measurement calibration.

The application of laser interferometry to precise length measurement is well known and several systems are commercially available from manufacturers such as Hewlett Packard, Spindler & Hoyer, and Renishaw. Most commercial interferometer systems currently available, make use of helium-neon lasers. Helium-neon lasers may be designed to operate in single longitudinal mode with a high degree of wavelength stability.

With the advent of diode lasers there are now strong commercial pressures to replace helium-neon lasers with diode lasers. Diode lasers are inexpensive, small and compact, efficient, and will run on low voltage current drives. Their main disadvantages are: propensity to mode hopping; wavelength changes with temperature and drive current; their lasing cavities are sensitive to small amounts of light reflected back into the cavity, for example off optical surfaces; and the coherence of their emitted light is restricted.

This invention is aimed at calibrating relatively unstable incremental length measuring apparatus and is specifically, but not exclusively, directed towards calibrating laser based length measuring interferometers which use diode lasers.

This invention addresses the problem of achieving high accuracy when using a relatively unstable laser wavelength. It also, by default, eliminates the need for correcting changes in wavelength brought about by changes in refractive index of air due to changes in atmospheric conditions, normally employed in the art.

By selecting an appropriate diode laser structure (for example index guided double heterostructure) mode hopping can normally be prevented by driving the diode with a stable pre-selected current and stabilising its operating temperature.

The basis of the invention is an optical cell which acts as standard length artifact or optical length artifact (OLA). The cell is used in conjunction with a collimated beam of light having a broad spectral band width. A suitable beam may be produced by collimating light emitted from, for example, a standard light emitting diode of the Gallium Aluminium Arsenide type, or a filament lamp. The cell operates by (although not exclusively) interference to impose a cyclically varying intensity profile across the wavelength spectrum of the light it transmits. A cell capable of producing this effect is a Fabry Perot etalon. The appropriate spectral properties are imposed on the beam after passing it through a Fabry Perot etalon cell. A Fabry Perot etalon is a multi-beam interferometer and as such produces a non-sinusoidal intensity profile across the spectrum of its output beam. A two beam interferometer (for example the Michelson) produces sinusoidal variations across the spectrum of the output beam. Virtually any interferometer type may be considered for use as a measurement artifact in this invention. The Fabry Perot etalon provides a convenient means of producing the desired effect.

An advantage of the Fabry Perot etalon is that a fixed mass of gas (air) may conveniently be sealed in a volume between its two reflectors (between which multiple reflections occur). This means that the optical path between the two reflectors (which defines the length of the optical artifact) will not be affected by changes in atmospheric conditions to a very high degree of accuracy. The only significant change in optical path length will be due to thermal expansion of the etalon which is accurately predictable using for example fused silica spacers.

It further may be an advantage in an embodiment of the invention for the space between the mirrors of an optical length artifact to be exposed or open to the atmosphere in order that its optical length is modified according to atmospheric conditions.

The effect is exploited in a different way and for a different purpose from the present invention by Erskine and Holmes (Nature,1995, volume 377 page 317). Erskine and Holmes use two similar, fixed path difference, interferometers in tandem. A low coherence light beam passes through each of the interferometers in turn with a measurement arm situated between the two interferometers. The instrument measures velocity by detecting a shift in the fringe pattern at the output of the second interferometer, by virtue of the Doppler effect. It is evident that the optical effect, exploited both in this invention and by Erskine and Holmes, cannot alone provide continuous linear incremental fringe counting required for linear distance measurement over reasonable measurement ranges.

This invention exploits the effect of passing a low coherence light beam through a fixed path difference interferometer purely as a means of providing a very accurate, built in, calibration for any incremental length measuring apparatus. It is more specifically suited to providing reference points and calibration for use with laser based distance measurement interferometers. Measurement ranges of laser based interferometers are inherently linear because they in effect count in wavelengths of light (normally half wavelengths). Measurements made, however, may not be accurate especially when the laser light is provided by a diode laser. This is because the wavelength of light from diode lasers is prone to vary with small changes in temperature and drive current, typically 70 parts per million per degree Celsius. Indeed the wavelength can be different each time the diode is switched on and stabilised at a fixed temperature and drive current.

It is an object of this invention to provide at least two fiducial or reference positions in the measuring range of the interferometer whose separations are known to a high degree of accuracy. This is provided by the optical length artifact. It is the intention of this invention to not only provide accurate reference points in the measurement range but also to provide on-board self calibration of linear measuring systems such as diode laser based interferometers.

The wavelength of the laser light is not actually required to be known, prior to taking measurements, in this invention. This is a distinguishing feature of the invention. Known arrangements strive to obtain knowledge of wavelength in order to obtain accurate length measurement.

A cyclically varying spectral profile may alternatively be produced using any suitable stable filtering means, for example, Solc or Lyot filter types.

A broad band (white light) light source has very low coherence and as such produces interference fringes only over a very short range of path differences. This small range may be utilised as a reference signature since the centre of the range is easily located by means of photo sensors to sense fringes. Only one such signature is normally generated in a variable path interferometer when using a broad spectral band light source. This occurs at the position of equal path lengths. When, however, the spectrum of broad band light is modified by first passing it through a filter, such as an interferometer of fixed path difference, for example a Fabry Perot etalon, then subsequent positions of detectable interference are found at path differences comparable with multiples of the spacing between the etalon mirrors. The number of different multiples of the spacing between the etalon mirrors corresponding to path differences at which subsequent detectable interference occurs, is comparable with the finesse of the etalon. This invention requires detectable interference to occur at at least two path differences, one of which may be the zero path condition, in order to derive at least two reference signatures. The physical separation of any two reference signatures is therefore determined by the geometrical and physical optical properties of the filter.

It should be noted that since only at least two positions of detectable interference are required for this invention, the finesse of the Fabry Perot etalon may be relatively low (eg. between 3 to 6) and in consequence does not require high grade

optics normally demanded in the construction of Fabry Perot etalons. Low finesse is also an advantage in terms of transmission of broad band radiation, which is proportional to the inverse of the finesse of the etalon.

It may be desirable, in some circumstances, to provide many reference signatures (for example ten) in the measuring range to provide ready calibration at any point along the measurement range. This would require the finesse of the etalon to be of the order of 10.

The principle of generating at least two reference signatures, by modifying spectral composition of a light source, may also be understood with reference to the field of Fourier transform spectroscopy.

According to the present invention there is provided apparatus for precise length measurement calibration comprising a linear length measuring interferometer having a broad spectral band source, a collimating means for producing a collimated incident beam, a beam splitter for producing part beams which, in use, pass along a reference arm and a measurement arm of the interferometer respectively, a reference reflector for reflecting the part beam passing along the reference arm, a measurement reflector for reflecting the part beam passing along the measurement arm, beam combining means for recombining the part beams reflected by the reference reflector and the measurement reflector, the measurement reflector being moveable to provide a measuring range; an optical length artifact for modifying the spectral composition of the incident beam or of one of the part beams or of a recombined beam in a way

that imposes a cyclically varying spectral intensity with changing wavelength across the broad spectral range of the light source; and fringe detection means providing at least two reference signatures throughout the measuring range spaced apart by an amount determined by the optical length artifact.

Preferred and/or optional features of the invention are set forth in claims 2 to 24.

The invention will now be described in more detail with reference to the following figures:

Figure 1 illustrates the salient features of one embodiment of the invention,

Figure 2 illustrates another embodiment of the invention,

Figure 3 shows typical reference signatures generated in the detection means of Figures 1 and 2,

Figure 4 shows a Fabry Perot etalon adapted as an optical length artifact with sealed cavity,

Figure 5 shows a Fabry Perot etalon whose cavity is exposed to atmospheric changes,

Figure 6 shows modified broad spectral band after transmission through the optical length artifact,

Figure 7 shows one embodiment of the invention incorporating a laser based length measuring interferometer,

Figure 8 shows an alternative site for the optical length artifact,

Figure 9 shows a further site for the optical length artifact,

Figure 10 shows another embodiment of the invention incorporating a laser based length measuring interferometer,

Figure 11 shows the salient features of the preferred embodiment.

Figure 12 shows the optical length artifact in the reference arm, reflecting light directly back to the beam splitter/combiner.

Referring to Figure 1, which illustrates the salient features of one embodiment of the invention, light emitted by a broad spectral band light source 1, conveniently a light emitting diode, is collimated by lens 2 before being modified by an optical length artifact 11 in the form of a Fabry Perot etalon shown in Figures 4 and 5. The Fabry Perot etalon imposes a cyclically varying profile across the broad spectral band of the light source as illustrated in Figure 6. After being modified by

its passage through the Fabry Perot etalon, the light enters a measuring interferometer of the Michelson type, having a beam splitter 4 for producing part beams 5R and 5M which pass along a reference arm 6R and a measurement arm 6M of the interferometer respectively, a reference reflector 7R for reflecting the part beam 5R passing along the reference arm 6R, a measurement reflector 7M for reflecting the part beam passing along the measurement arm 6M, beam combining means 8 for recombining the part beams 5R and 5M and a fringe detector 9. The measurement reflector 7M is movable over a measurement range 10. Normally, a measuring interferometer of this type produces detectable fringes only over a small measuring range, typically 5-10 microns, when using a broad spectral band source. When the spectrum of the source is modified using a Fabry Perot interferometer, short bursts of detectable fringes are produces at several places along the measuring range 10, as illustrated in Figure 3. The central maxima of the detectable fringes is located by electronic means known in the art.

The Fabry Perot etalon 11 may be used as an optical length artifact in two distinct ways: either a fixed mass of gas is sealed in the etalon cavity as illustrated in Figure 4; or the etalon cavity is exposed or open to the atmosphere to allow the refractive index of the air within the cavity to change with change in atmospheric conditions as illustrated in Figure 5. In the former case the measured **optical** separation between the reference signatures is precisely related to the separation of the Fabry Perot etalon mirrors. In the latter case the measured **physical** separation between the reference signatures is precisely related to the separation of the Fabry Perot etalon mirrors. The latter is generally favoured as it automatically compensates

for changes in the refractive index of air. The former can be used in conjunction with atmospheric monitoring to enable a correction to be made to measured displacements.

In the preferred embodiment of the invention, the Fabry Perot etalon cell shown in Figure 5 comprises two partially reflecting and partially transmitting surfaces 21,24 which may be plane or configured as a confocal resonator, supported on an appropriate substrates 20, for example fused silica. The partially reflecting surfaces (mirrors) are spaced apart by a convenient distance (eg. 50 mm) by a spacer tube 22 also fabricated in fused silica. In this embodiment, the etalon mirrors are exposed to changes in the atmosphere by providing a breather tube 26. An air filter 25 is located in the breather tube to prevent contamination of the etalon mirrors.

Since displacement of the measuring reflector 7M produces a change in path length of twice the displacement of the reflector, reference signatures are separated by 50 mm, in the measuring range, when the separation of the mirrors in the optical length artifact (Fabry Perot etalon) are 50 mm. Reflectance values of the etalon mirrors of 0.6 (0.4 transmitting) produce a suitable etalon finesse of around 6.

Figure 4 shows the mirror substrates hard sealed 23, or fused, to the spacer tube in order to trap a fixed mass of air (or gas) in the etalon cavity.

Fused silica is cited for its low and predictable coefficient of thermal expansion and also because it may be fabricated as a tube and is fusible to the mirror substrates. Any other material with appropriate properties may be used for mirror

substrates and spacer tube.

The measured distance between successive reference signatures is an optical distance in the measuring range which is precisely equal to the optical separation between the etalon mirrors. If the etalon is sealed, as shown in Figure 4, its optical length only varies with the thermal expansion of its mirror spacer. Its optical length must therefore be determined at an accurately known temperature, so that its optical length can be calculated for any operating temperature.

If the etalon is open to atmosphere, as shown in Figure 5, its physical length is always equal to the separation of successive reference signatures in the measuring range. In this case either: the physical length (not optical length) of the etalon must be measured at a known temperature; or the separation between reference signatures in the measuring range accurately determined using an auxiliary precision interferometer, for example an atmospheric corrected Iodine stabilised helium-neon laser, from which the physical length of the etalon is deduced at the measured temperature. The apparatuses of Figures 1 or 7 may be adapted for this purpose.

Figure 2 shows a length measuring interferometer incorporating an alternative optical length artifact 11 in the form of a general fixed path difference interferometer. The optical length artifact shown in Figure 2 represents any form of two beam fixed path difference interferometer. The general fixed path interferometer may be variations or combinations of any of the following types:

Michelson

Mach-Zehnder

Cyclic

Semi-cyclic

Grating

Shear plate

Figure 7 (a) and (b) shows two views of the above described apparatus integrated into a laser length measuring interferometer. In this embodiment, the laser source is a diode laser 16 located within a temperature controlled enclosure 14 which prevents mode hopping. A collimated beam 15 from this laser enters the measuring interferometer without necessarily, and preferably not, passing through the etalon. The two views in Figure 7 show how the respective beams from the diode laser and from the broad band source are kept separate while sharing the same measuring interferometer. This is facilitated using cube corner retroreflector 7R and 7M in the reference arm 6R and measurement arm 6M respectively.

Retroreflectors in the respective arms of the interferometer are, used typically in the art, cube corner reflectors, which are insensitive to angular misalignment. Cube corner reflectors may also be used to spatially separate the incident beam from the return beam. This fact is used, in the embodiment shown in Figure 7, as a means of separating the measuring (laser) beam from the broad band beam.

Alternatively, the respective beams from the diode laser and the broad band source may be laterally displaced (out of the plane of the diagram). In this case, the retroreflectors 7R and 7M are 90 degree porro type reflecting prisms.

Figures 8 and 9 show alternative sites for the optical length artifact in the reference arm and measurement arms of the measuring interferometer respectively.

Figure 10 shows the combining of the laser and broad band beams prior to entering the measuring interferometer, and their subsequent separation prior to their respective fringe detection. In this case beam combiner 18 and separator 17 are appropriate dichroic filters. The optical length artifact could be located between the beam combiner 8 and the separator 17 instead of in the incident beam or the reference or measurement arms.

Figure 11 shows the preferred embodiment of the invention in which the etalon is located in the reference arm of a Michelson interferometer. In the preferred embodiment, the etalon is reflective, which returns the light back along the same path in the reference arm. The measuring arm of the interferometer has a corresponding mirror 30 which similarly reflects light back along the same path in the measuring arm, and the light in this arm is subsequently recombined with the light in the reference arm at the beam splitter/combiner in order for interference to occur, and be detectable by the detector 9. Such an arrangement is commonly referred to as a double pass interferometer and has the advantage that, once set up, fringe visibility is unaffected by lateral displacement or rotation of cube corner retroreflectors in

either arm of the interferometer. Because it is double path, interference signatures produced in the Michelson interferometer by virtue of the etalon are separated in distance along the measuring arm by half the length of the etalon.

Figure 12 shows an embodiment of the invention in which the optical length artifact is located in the reference arm, with its mirrors reflecting light back to the beam splitter/recombiner, without the use of additional reflecting surfaces in the reference arm. This embodiment retains double pass in the measuring arm which benefits from displacement tolerance of the associated retroreflector.

The beam combiner 8 used in the preferred embodiment of this invention, and also in any laser length measuring interferometer used in conjunction with this invention, is a non-polarising type proposed by Raines and Downs (Optica Acta, 1978, volume 25, number 7, pages 549 to 558) which imparts an optical phase delay such that reflected and transmitted fringe modulations are at 90 degrees to each other, ie. they are in phase quadrature. Phase quadrature signals are used for up and down incremental counting and form the basis of position measurement known in the art.

The 90 degree phase delay is also useful when deriving a reference signature of the type shown in Figure 3. The fringe detection means 9 detects fringes generated at the beam combiner 8 both transmitted and reflected by the beam combiner. These two signals are subsequently subtracted to provide reference signatures shown in Figure 3. By imparting a phase delay of 90 degrees between the two signals as provided by the method of Raines and Downs, the central region of a

reference signature is made to pass through zero which, it is known in the art, provides a very accurate means of position detection.

The laser length interferometer is calibrated by counting the number of signals generated by the laser length interferometer as the measurement reflector 7M is moved between detectable fringes produced by the optical length artefact.

The invention may be adapted for use with polarising length measuring interferometers known in the art.

CLAIMS

1. Apparatus for precise length measurement calibration comprising a linear length measuring interferometer having a broad spectral band light source (1), a collimating means (2) for producing a collimated incident light beam (3), a beam splitter (4) for producing part beams (5R, 5M) which, in use, pass along a reference arm (6R) and a measurement arm (6M) of the interferometer respectively, a reference reflector (7R) for reflecting the part beam passing along the reference arm, a measurement reflector (7M) for reflecting the part beam passing along the measurement arm, beam combining means (8) for recombining the part beams (5R and 5M) reflected by the reference reflector and the measurement reflector, the measurement reflector being movable to provide a measuring range (10); an optical length artifact (11) for modifying the spectral composition of the incident light beam, or of one of the part beams, or of a recombined beam, in a way that imposes a cyclically varying spectral intensity with wavelength across the broad spectral band of light originating from the light source; and the fringe detection means (9) providing at least two position reference signatures throughout the measuring range spaced apart by an amount determined by the optical length artifact (11).

2. Apparatus according to claim 1, in which the optical length artifact (11) is a multiple beam interferometer.

3. Apparatus according to claim 2, in which the optical length artifact (11) is a Fabre Perot interferometer.

4. Apparatus according to claim 1, in which the optical length artifact (11) is a two beam interferometer.

5. Apparatus according to claim 4, in which the optical length artifact (11) is a two beam interferometer, having fixed path difference, of any of the generic types: Michelson; Mach-Zehnder; Cyclic; Semicyclic; Grating; Shear plate.

6. Apparatus according to claim 3, in which the mirrors (21,24) of the Fabry Perot interferometer are separated using a stable material (22) whose coefficient of thermal expansion is known to an appropriately good degree of accuracy.

7. Apparatus according to claim 6, in which the mirrors (21,24) are separated by a cylindrical tube (22).

8. Apparatus according to claim 6 or claim 7, in which the stable material is fused silica.

9. Apparatus according to claim 6 or claim 7, in which the stable material is a proprietary low expansion material such as ULE and Zerodur.

10. Apparatus according to any one of the claims 7, 8 or 9, in which the cylindrical tube (22), together with the etalon mirrors (21,24), seal and enclose a fixed mass of gas inside the etalon cavity.

11. Apparatus according to any one of claims 1 to 9, in which the gas which determines the optical path length of the optical length artifact is representative of the ambient air conditions, in terms of refractive index.

12. Apparatus according to any one of the claims 7, 8, or 9, in which the cylindrical tube (21,24), together with the etalon mirrors, enclose a fixed volume of gas inside the etalon cavity, but whose condition is allowed to vary as the ambient air conditions so that the refractive index of the gas between the mirrors is representative of the refractive index of the ambient air in which interferometric length measurement is made.

13. Apparatus according to claim 12, in which an atmospheric breather tube (26) is provided to allow the air volume inside the etalon cavity to communicate with the ambient atmosphere.

14. Apparatus according to claim 13, in which the atmospheric breather tube (26) is fitted with an air filter (25) to prevent contamination of the etalon mirrors.

15. Apparatus according to any one of the preceding claims, in which the optical length artifact (11) is located to modify the spectral composition of the incident beam.

16. Apparatus according to any one of claims 1 to 14, in which the optical length artifact (11) is located to modify the spectral composition of one of the part

beams (5R or 5M).

17. Apparatus according to any one of claims 1 to 14, in which the optical length artifact is located to modify the spectral composition of a recombined part beam.

18. Apparatus according to any one of the preceding claims, in combination with a laser interferometer comprising a laser source (16) for providing a collimated laser beam (15) which, in use, passes, together with the broad band light beam, through a common length measuring interferometer, for the purpose of obtaining continuous trains of cyclical quadrature signals, in the measuring range, from which incremental length measurements are made; at the same time obtaining at least two position reference signatures from the broad band light, in said range.

19. Apparatus according to claim 18, in which the laser source (16) is a helium-neon laser.

20. Apparatus according to claim 18, in which the laser source (16) is a diode laser having a mode structure which endows the laser beam with an appropriate level of coherence for the purpose of interferometric length measurement.

21. Apparatus according to claim 1, in which the optical length artifact (11) is an optical filter

22. Apparatus according to claim 21, in which the optical length artifact (11) is a polarising optical filter of the Lyot or Solc types.

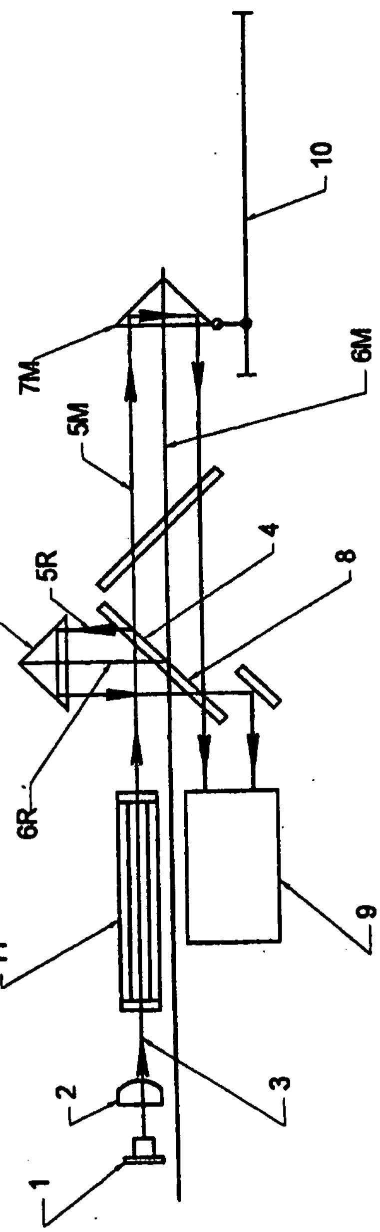

Figure 1

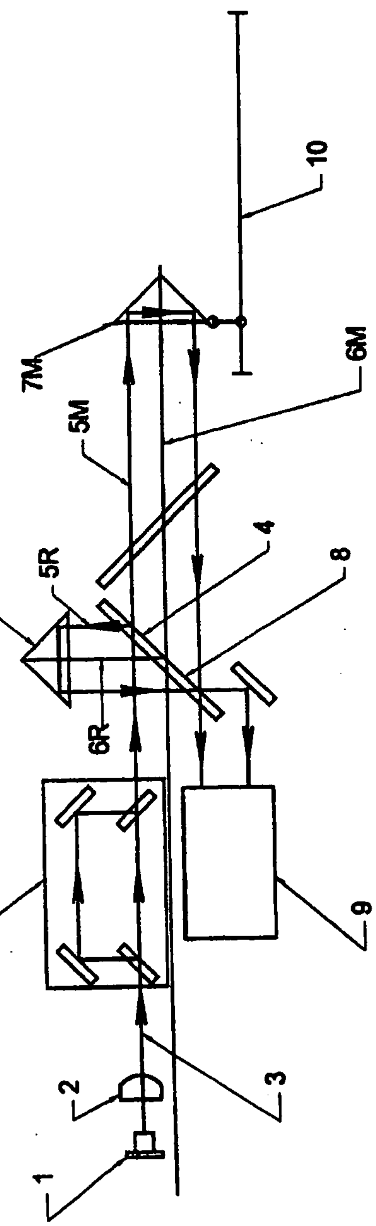

Figure 2

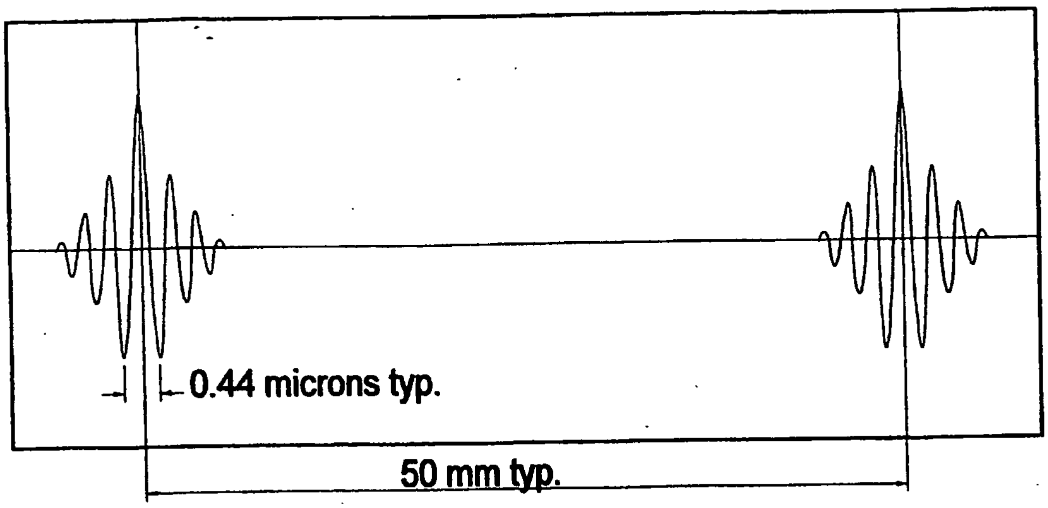

Figure 3

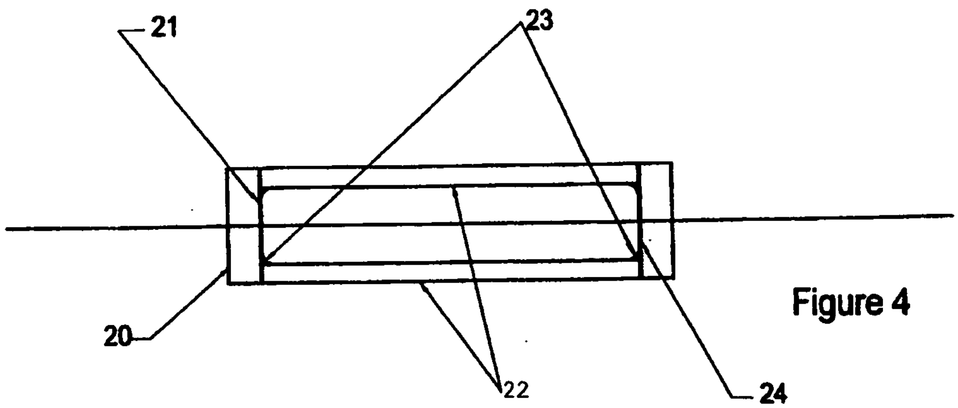

Figure 4

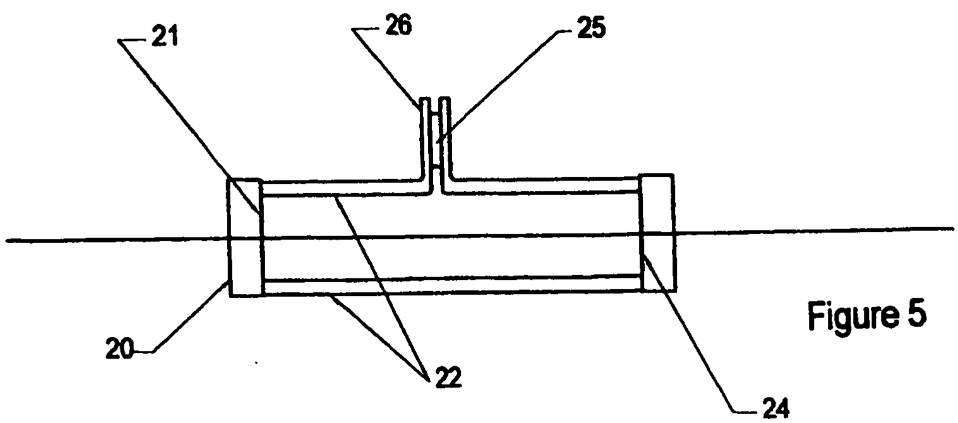

Figure 5

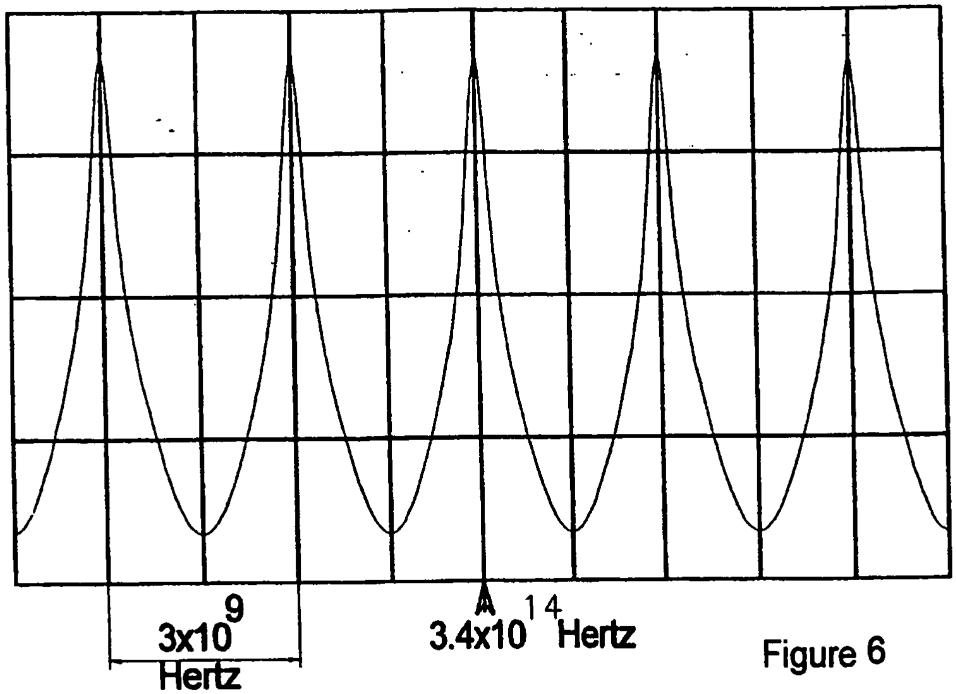

Figure 6

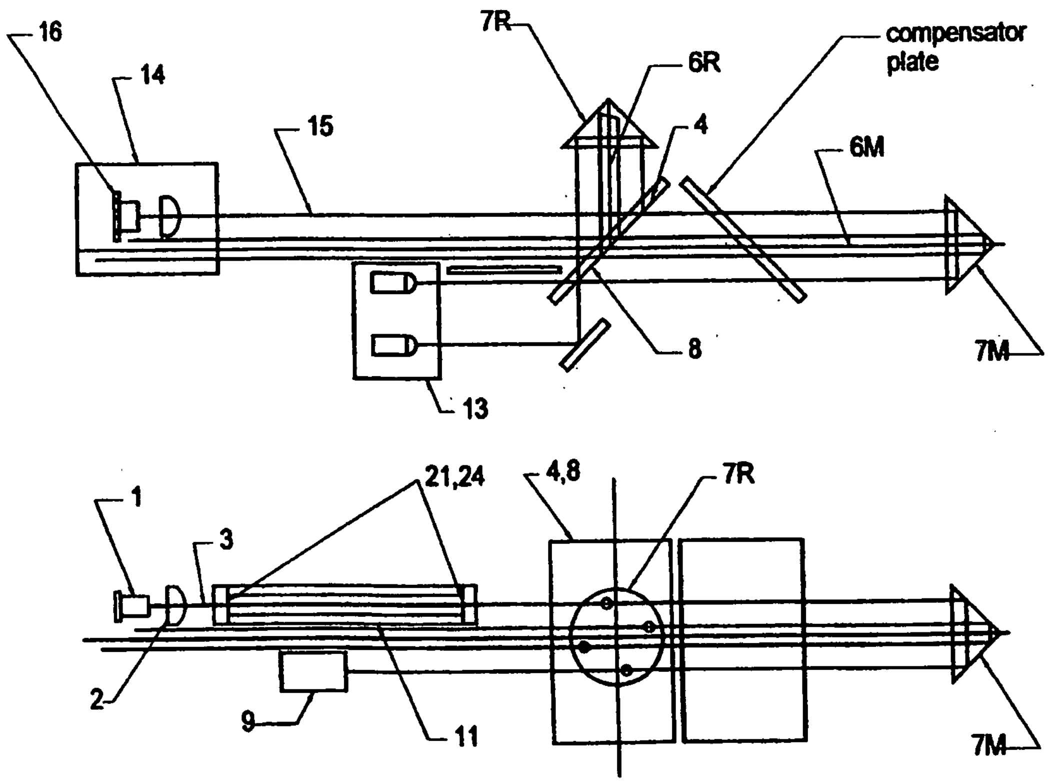

Figure 7(a) and (b)

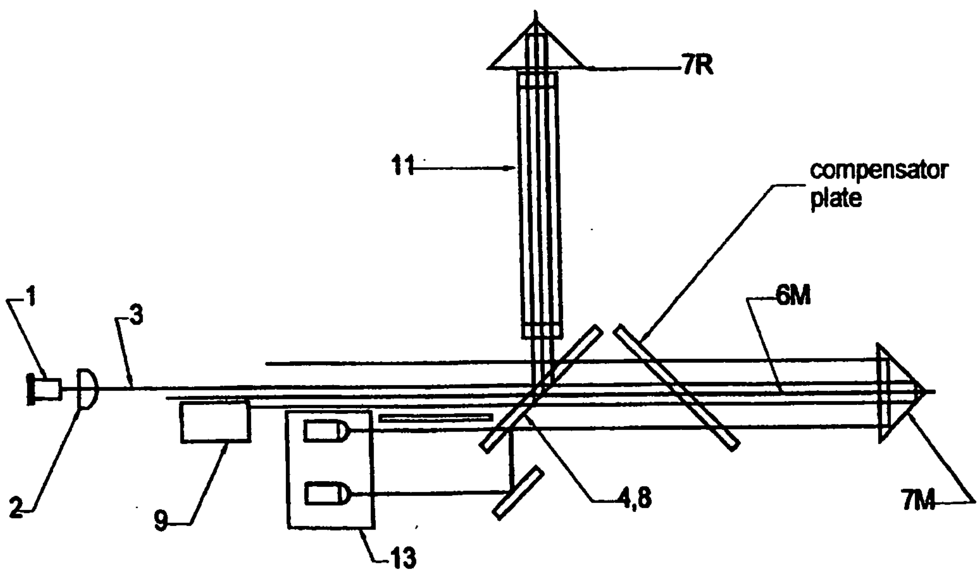

Figure 8

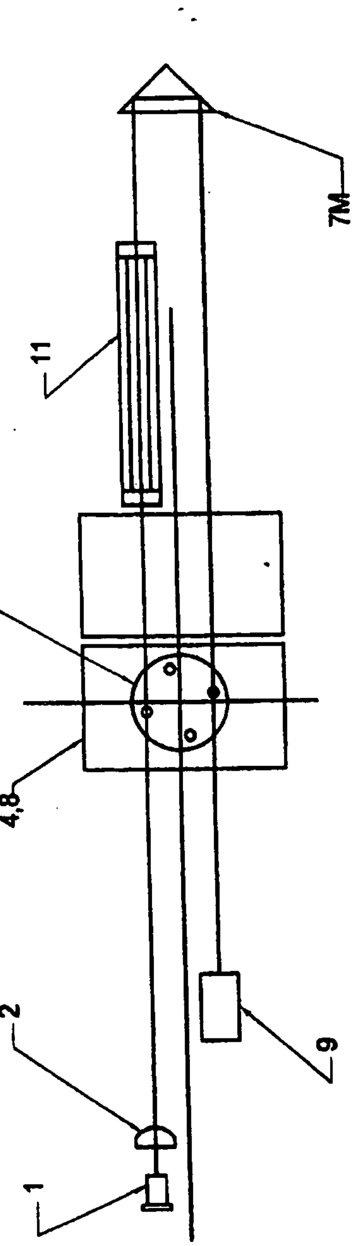

Figure 9

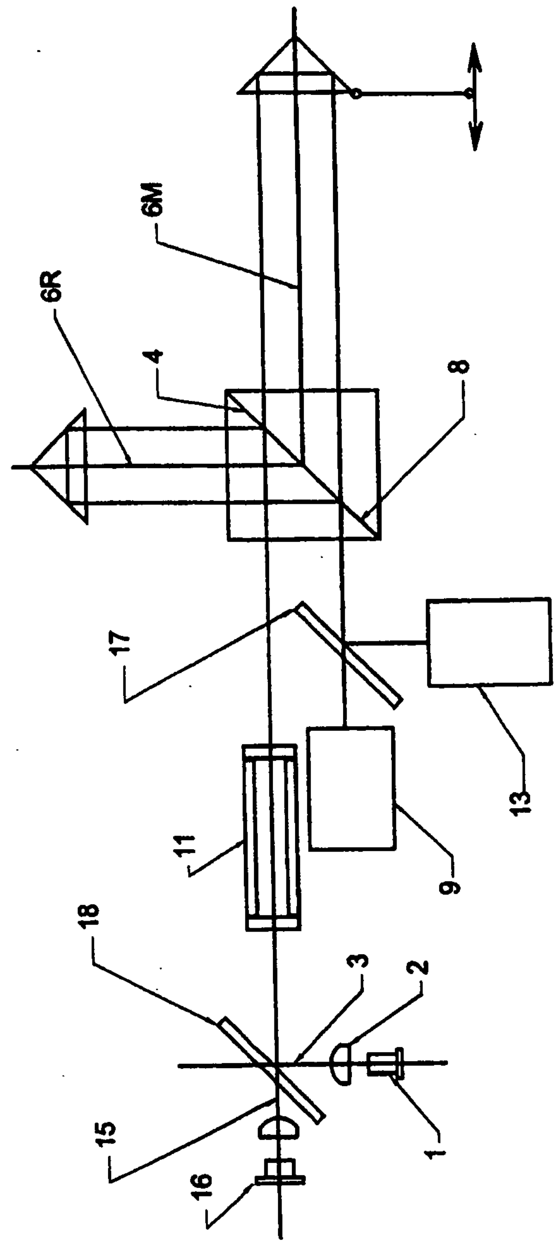

Figure 10

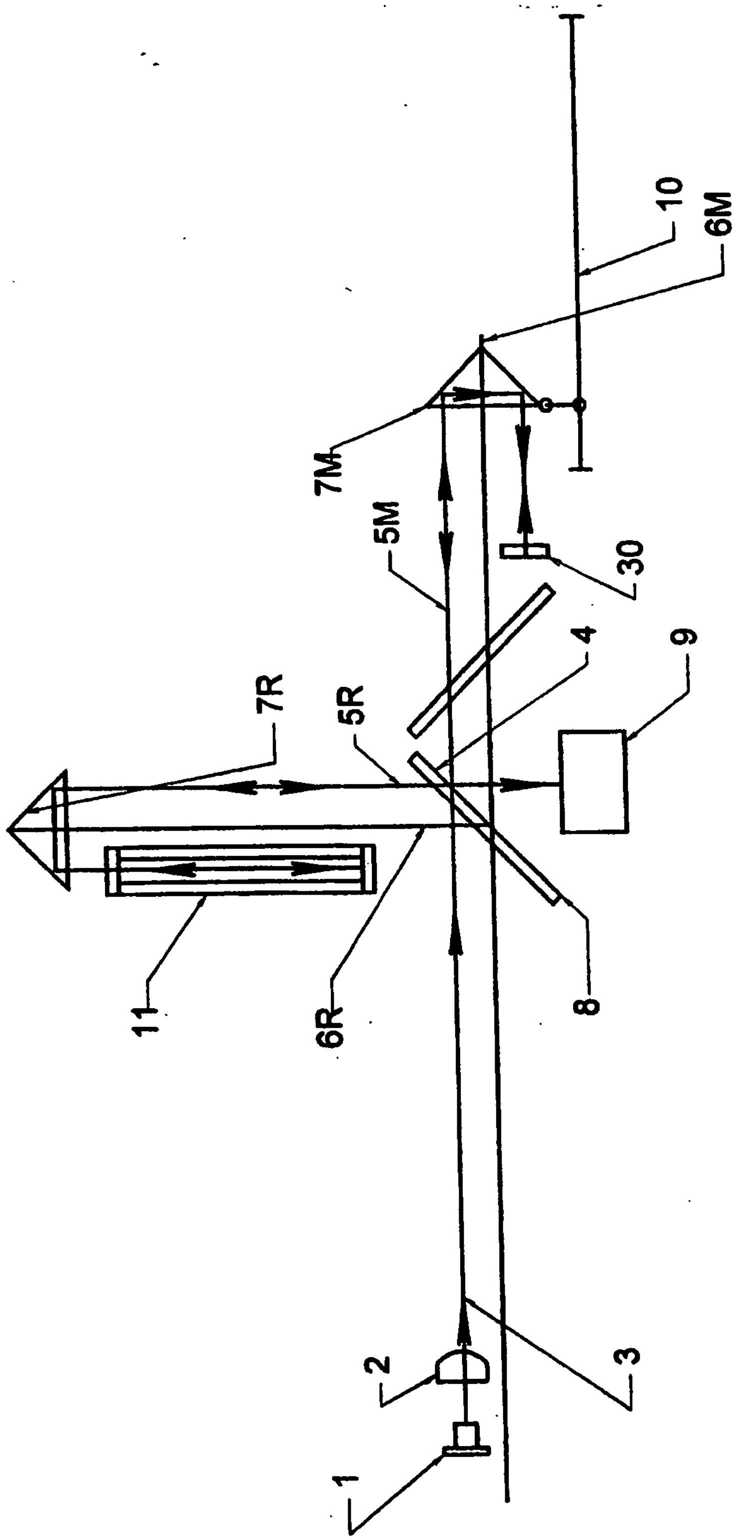

Figure 11

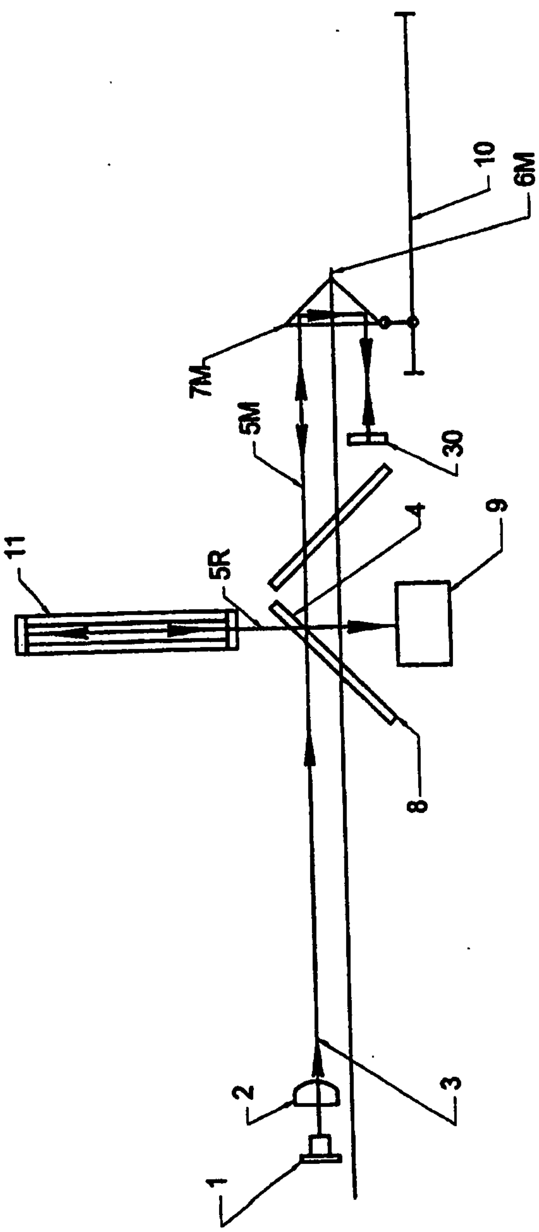

Figure 12

I[redacted]RNATIONAL SEARCH REPORT

In[redacted]al Application No
PCT/GB 98/00365

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B9/02

According to International Patent Classification(IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	WO 90 11485 A (W. TABARELLI) 4 October 1990 see introduction; see page 7, line 9 - page 10, line 17; figures 1-3 see page 12, line 24 - page 12, line 32; figure 6 ---	1-3,6, 11,15 7-10, 12-14
X A	DE 12 04 838 B (OLYMPUS K.K.K.K) 11 November 1965 see introduction; see column 4, line 13 - column 7, line 28; figures 2-6 --- -/--	1-3,6, 11,15,17 7-10,12, 14

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

* Special categories of cited documents :

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
11 May 1998	18/05/1998

Name and mailing address of the ISA	Authorized officer
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